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Finding the Most Sustainable Wind Farm Sites with a Hierarchical Outranking Decision Aiding Method

Arayeh Afsordegan · Luis Del Vasto-Terrientes · Aida Valls · Núria Agell · Mónica Sánchez

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Abstract This paper considers the problem of finding suitable sites for wind farms in a region of Catalonia (Spain). The evaluation criteria are structured into a hierarchy that identifies several intermediate sub-goals dealing with different points of view. Therefore, the recent ELECTRE-III-H hierarchical multi-criteria analysis method is proposed as a good solution to help decision-makers. This method establishes an order among the set of possible sites for the wind farms for each sub-goal. ELECTRE-III-H aggregates these orders into an overall order using different parameters. The procedure is based on the construction and exploitation of a pairwise outranking relation, following the principles of concordance (i.e. majority rule) and discordance (i.e. respect for the minority opinions). This paper makes two main contributions. First, it contributes to the ELECTRE-III-H method by studying its mathematical properties for the construction of outranking relations. Second, the case study is solved and its results show that we can effectively represent and manage the overall influence of the various criteria on the global result at different levels of the hierarchy. The paper compares different scenarios with strict, normal, and optimistic preference, indifference and veto thresholds. Results show that the best site differs for technical, economic, environmental, and social intermediate criteria. Therefore, the best overall solution changes depending on the preference and veto thresholds fixed at the intermediate level of the hierarchy.

Keywords Hierarchical assessment · Multi-criteria decision aid · ELECTRE · sustainable energy · wind farm location

1 Introduction

In the last decade, integrating new energy sources and modifying the use of fossil fuels has become essential for changing the energy supply system. Energy production involves several long-term practices with environmental impacts and is one of the causes of global warming and climate change. Climate change is occurring even faster than expected, and a 50% reduction in CO_2 emissions by 2050 may be insufficient to prevent dangerous climate change (IEA, 2013). To confront this damage to the environment, several planning strategies have been utilized to accomplish

Arayeh Afsordegan
ESADE Business School, Ramon Llull University
E-mail: arayeh.afsordegan@esade.edu

Luis Del Vasto-Terrientes · Aida Valls
Departament d'Enginyeria Informatica i Matematiques, Universitat Rovira i Virgili
E-mail: {luismiguel.delvasto;aida.valls}@urv.cat

Núria Agell
ESADE Business School, Ramon Llull University
E-mail: nuria.agell@esade.edu

Mónica Sánchez
Department of Mathematics, UPC-BarcelonaTech
E-mail: monica.sanchez@upc.edu

the Kyoto protocol. There is a consensus that because of the limitations of fossil fuel supply, as well as the environmental deterioration arising from its use, other sources of energy should be considered (European Commission, 2010; Evans et al., 2009; Carrera and Mack, 2010; Jing et al., 2012; Streimikiene et al., 2012).

Renewable energy sources, such as wind, are one of the most important and strategic solutions for future energy production. Wind energy is a crucial field in the quest for renewable energy given its increasingly positive impact on sustainability. Apart from being a major source of renewable energy, wind farms are quick and easy to build, produce no emissions, and make few resource demands (Georgopoulou et al., 1998; Radics and Bartholy, 2008). This combination of virtues makes wind energy one of the most promising tools for confronting global warming. Studies are currently focusing on improving wind turbines and the impact of wind farm siting (Lee et al., 2009). This type of analysis is important for investment in this sector. For investment to take place, various stakeholders participate in the decision about renewable projects, giving their different points of view. In particular, socio-economic actors (stakeholders) such as town councils, platforms, associations and neighbors should be also included in the process to discuss the pros and cons of various projects, and construct new alternatives to the current arrangements. Thus, the assessment and selection of the best site in a given area must take into account several sustainability issues, involving technical, economic, environmental, and social criteria. Applying well-founded mathematical methods may aid decision-makers in the energy area to find the most appropriate solutions.

This paper considers the problem of finding suitable sites for wind farms in a region of Catalonia (Spain), in terms of a hierarchy of criteria. This case study, which was the part of the Spanish research project detailed in Gamboa and Munda (2007), analyzes seven projects with different locations for the construction of wind turbines. Given public concern about the impact of this wind farm, the options considered were based on combining information from participatory processes, interviews, and a review of the projects in the regions of Urgell and La Conca de Barberà. Considering the multiple conflicting factors involved in the decision process to find the best wind park location, a tool to better analyze each of these sub-problems is proposed in this paper.

In the literature, the decision analysis methods used in this type of problems consider all the criteria at the same level. The models then search for a consensus of those criteria using a mathematical model that can aggregate the performance value of the options for each criterion into an overall performance, which is used to obtain a final ranking of the options (Afgan and Carvalho, 2002; Aras et al., 2004; Papadopoulos and Karagiannidis, 2008; Wang et al., 2009; Wimmler et al., 2015), or to establish a ranking between the options (Goletsis et al., 2003; Afsordegan et al., 2016a,b). In this paper, we propose a different approach to help decision-makers find the best location for a wind farm. Due to the diverse nature of the indicators that must be considered, we propose organizing the set of criteria following a hierarchical structure. The root node corresponds to the overall goal (global evaluation of all criteria), and the intermediate criteria represent subgoals focused on a certain aspect of the problem (e.g. environmental concerns, social concerns, technical issues, etc.). Finally, the lowest level of elementary criteria corresponds to the basic indicators available of each sub-goal.

There are only a few decision aiding methods that analyze at different levels of generality, providing partial results at each intermediate node of the hierarchy. In this paper, the ELECTRE-III-H method proposed recently in Del Vasto-Terrientes et al. (2015b) is studied. ELECTRE-III-H is able to construct a partial pre-order at different levels of a hierarchy of criteria. With this tool, the decision-maker may establish the overall suitability and preference relations between different sites in relation to several sub-parts of the problem. The most sustainable solution in different scenarios is sought using a hierarchy with an elementary level (including indicators), intermediate level (including criteria), and finally, a goal level.

The main aim of this paper is to demonstrate the usefulness of the hierarchical ELECTRE-III-H method for decision problems with a hierarchy of criteria with respect to the classical flat approach, where all criteria are aggregated simultaneously. Several applications have a natural hierarchical structure but are later solved with the classic approach, such as the case of evaluating wind farm locations. Working with a hierarchical structure facilitates a more detailed analysis of the various dimensions of the problem, which may correspond to different needs for different stakeholders (e.g. authorities, environmental protection agencies, or even local residents). To do so, a first contribution is made with the characterization of the outranking relation for each of the possible binary relations found in partial-preorder: preference, indifference and incomparability. Then, the consistency between the binary relations obtained for different criteria and the calculated outranking relation is shown. Finally, the study of the mathematical properties of ELECTRE-III-H taking into account the usual conditions considered in social choice methods is given.

The second contribution is the transformation of the model used in a case study performed by Gamboa and Munda (2007) by using a hierarchical approach. Using the aforementioned ELECTRE-II-H, a complete study of various scenarios is performed, comparing the results in different situations representing diverse points of view. This study shows how each sub-goal may influence the global result using the hierarchical outranking method. The effectiveness of the hierarchical approach is presented with a robustness analysis of the solutions obtained at different levels. Finally, the proposed solution is a choice of location that moves the windmills away from the villages (whose inhabitants oppose the windfarms).

The paper is organized in 6 sections. After this introduction, Section 2 and 3 present the ELECTRE-III-H method and the study of its properties. Section 4 explains the problem of assessing wind farm locations, presenting the set of criteria and their hierarchical organization. Also the case study in Catalonia is introduced. Section 5 shows the different analysis done on this case study, using several scenarios with different configuration at the different levels of the hierarchy. Results are compared and discussed. Finally, section 6 summarizes the main conclusions and proposes some future lines of work.

2 Preliminaries: The ELECTRE-III-H Method

ELECTRE-III-H is a multi-criteria decision-making method proposed in Del Vasto-Terrientes et al. (2015b) that allows the decomposition of the decision problem into smaller sub-problems of interest in a hierarchy of criteria, imitating the hierarchical decomposition procedure for decision making that humans do. This hierarchy permits the arranging of criteria into different levels of generality in a tree-like structure, suitable when the decision-maker is not only interested in analysing overall suitability but also preference relations between alternatives (e.g., wind farm sites) regarding to more specific sub-criteria that refer to some particular aspects of the problem. ELECTRE-III-H has been successfully applied in different fields, such as Website management (Del Vasto-Terrientes et al, 2015a) and environmental sciences (Del Vasto-Terrientes L. et al., 2016).

ELECTRE-III-H distinguishes the following 3 types of criteria in a hierarchy:

- Root criterion: Unique criterion defined at the top of the hierarchy, representing the global or most general goal.
- Elementary criteria: Set composed of the most specific criteria, found at the bottom level of the hierarchy. They correspond to concrete the indicators used by the decision-maker to directly evaluate the alternatives.
- Intermediate criteria: Set of criteria defined between the root and elementary criteria, representing sub-goals at different levels of generality (the number of layers of intermediate criteria is not limited).

Note that in our approach all elementary and intermediate criteria are considered pseudo-criteria, with two threshold functions to represent uncertainty on the preference establishment: named indifference threshold $q_j(.)$ and preference threshold $p_j(.)$ (Colson and Bruyn, 1989). In addition, a third threshold to give veto power is used $v_j(.)$. Hereinafter, the set G denotes the set of all intermediate and elementary criteria.

The ELECTRE-III-H method follows the classical outranking ELECTRE procedure at all subsets of related criteria (Roy, 1996), which entails two steps: (1) The construction of outranking relations and (2) exploitation of these relations by distillation, resulting in a partial pre-order. The outranking relation S is built taking into account the set G. Let A be the set of alternatives. Given an ordered pair of alternatives $(a, b) \in A \times A$, alternative a outranks alternative b if a outperforms b on enough criteria of sufficient importance, and a is not outperformed by b with a significantly inferior performance on any single criterion. The outranking relation aSb is constructed on the basis of two tests:

- Concordance test: The relation aSb must be supported by a sufficient majority of criteria,

– Discordance test: None of the criteria should strongly be against the assertion aSb. Otherwise, the relation aSb does not hold.

The credibility $\rho(a, b)$ of the outranking is determined by comparing a and b and obtaining a partial concordance index c_j and a partial discordance index d_j for each criterion g_j in set G.

From the elementary indicators ELECTRE-III-H generates a preference structure of alternatives in the form of partial pre-orders. These partial pre-orders can be used to compare the suitability of the alternatives at the different intermediate layers. The partial pre-order depends on how well they perform on the particular subsets of criteria and how important each criterion is to the decision-maker. Following bottom-up procedure, ELECTRE-III-H builds an order structure at each non-elementary criteria. For instance, following Figure 1, classic ELECTRE-III is applied at elementary criteria for each subset of criteria $\{g_{1.1.1}, g_{1.1.2}, g_{1.1.3}\}$, $\{g_{1.2.1.1}, g_{1.2.1.2}\}$, and $\{g_{1.2.2.1}, g_{1.2.2.2}\}$, resulting in the first partial pre-orders at their direct parents. Next, a partial pre-order at $g_{1.2}$ is computed from the partial pre-orders obtained for $g_{1.2.1}$ and $g_{1.2.2}$, and so on up to the root.

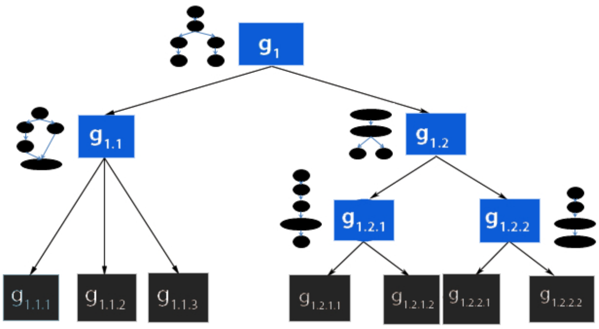

Fig. 1: The ELECTRE-III-H process

To aggregate the information obtained from partial pre-orders, ELECTRE-III-H proposes the calculation of partial concordance and discordance indices of the alternatives based on:

– Binary relations. For each partial pre-order O_j, four possible binary relations for a pair (a, b) exist: Preference (aPb), Inverse Preference $(aP^{-}b)$, Indifference (aIb), and Incomparability (aRb).
– Rank Order Value $\Gamma_j(a)$. It counts the number of alternatives belonging to A that are preferred to alternative a for the partial pre-order O_j.

Following the example presented in Figure 1, let us consider the partial pre-order generated in $O_{1.1}$ and presented in Figure 2. Based on the binary relations existing in the partial pre-order $O_{1.1}$, a preference relation matrix can be built as shown in Table 1. The last column shows the *Rank Order Value* of each alternative.

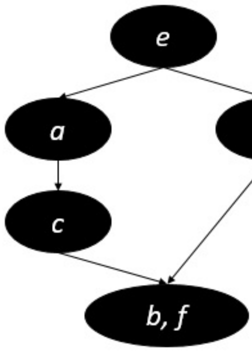

Fig. 2: Partial pre-order generated on $O_{1.1}$

Table 1: Preference matrix and *Rank Order Values* from partial pre-order $O_{1.1}$

	a	b	c	d	e	f	$\Gamma_{1.1}$
a	I	P	P	R	P^-	P	1
b	P^-	I	P^-	P^-	P^-	I	4
c	P^-	P	I	R	P^-	P	2
d	R	P	R	I	P^-	P	1
e	P	P	P	P	I	P	0
f	P^-	I	P^-	P^-	P^-	I	4

Three thresholds, based on either the performance values of the elementary criteria, or the rank order values of the intermediate criteria, are used to calculate the partial concordance and partial discordance indices:

- Indifference threshold (q_j): below which the decision-maker is indifferent to the evaluation of alternative a and alternative b on criterion g_j.
- Preference threshold (p_j): above which the decision-maker shows a clear strict preference in favor of alternative a over b on criterion g_j.
- Veto threshold (v_j): where a discordant difference larger than the veto in favor of b with respect to alternative a will require to negate the outranking relation aSb.

At the bottom level, these thresholds are based on the performance values of the alternatives on the elementary indicators. At the upper levels, these thresholds are defined with respect to the rank order value of the alternatives in the partial pre-orders.

For each pair of alternatives (a, b), the binary relations $\phi \in \{P, I, P^-, R\}$ connect them in O_j on the $j-th$ criterion. Considering this, partial concordance and discordance indices from partial pre-orders are calculated on the basis of the relation ϕ between a and b as follows: [1]

- When aPb or aIb (preference or indifference): Both relations support the assertion aSb. Therefore, the partial concordance index is set to its maximum value while the partial discordance index to its minimum.

$$c_j(aPb) \text{ and } c_j(aIb) = 1 \tag{1}$$

$$d_j(aPb) \text{ and } d_j(aIb) = 0 \tag{2}$$

[1] For the sake of simplicity, in the rest of the paper, a notation based on the preference relation between a and b will be used, such that $c_j(a, b) = c_j(a\phi b)$ and $d_j(a, b) = d_j(a\phi b)$.

– When $aP^{-}b$ (inverse preference): The assertion aSb is not supported by the inverse preference relation. However, as the intermediate criteria are considered pseudo-criteria, some tolerance degree may be defined by the decision-maker.

$$c_j(aP^{-}b) = \begin{cases} 1 & \text{if } \Gamma_j(a) - \Gamma_j(b) \leq q_j(a) \\ 0 & \text{if } \Gamma_j(a) - \Gamma_j(b) > p_j(a) \\ \frac{p_j(a)-(\Gamma_j(a)-\Gamma_j(b))}{p_j(a)-q_j(a)} & \text{otherwise} \end{cases} \quad (3)$$

$$d_j(aP^{-}b) = \begin{cases} 1 & \text{if } \Gamma_j(a) - \Gamma_j(b) > v_j(a) \\ 0 & \text{if } \Gamma_j(a) - \Gamma_j(b) \leq p_j(a) \\ \frac{\Gamma_j(a)-\Gamma_j(b)-p_j(a)}{v_j(a)-p_j(a)} & \text{otherwise} \end{cases} \quad (4)$$

– When aRb (incomparability): A preference relation between the alternatives evaluated is impossible to be defined. Thus, we consider the equiprobability of aRb to turn into aPb, $aP^{-}b$ and aIb. As the two first cases support aSb while the third does not, we assume a partial concordance index base value k^c=2/3 and a partial discordance index base value k^d=1/3. Also, a variable α has been introduced to define the maximum degree of change of the base values k^c and k^d.

$$\text{if } \Gamma_j(a) - \Gamma_j(b) \leq p_j(a), \text{ then } \begin{cases} c_j(aRb) = k^c + \frac{(\Gamma_j(b)-\Gamma_j(a)-q_j(a))\times\alpha}{p_j(a)-q_j(a)+(n-2)} \\ d_j(aRb) = 0 \end{cases} \quad (5)$$

$$\text{if } \Gamma_j(a) - \Gamma_j(b) > p_j(a), \text{ then } \begin{cases} c_j(aRb) = 0 \\ d_j(aRb) = k^d + \frac{(\Gamma_j(a)-\Gamma_j(b)-v_j(a))\times\alpha}{v_j(a)-p_j(a)+(n-2)} \end{cases} \quad (6)$$

An overall concordance $c(a, b)$ is calculated as a weighted average of the partial concordances. Next, the calculation of the credibility degree $\rho(a, b)$ of the outranking relation is done by including the criteria $g_j \in J$, being $J = \{g_j | d_j(a, b) > c(a, b)\}$, which is the set of criteria that have a discordance value greater than the overall concordance.

$$\rho(a, b) = \begin{cases} c(a, b) & \text{if } d_j(a, b) \leq c(a, b), \forall j \\ c(a, b) \cdot \prod_{j \in J(a,b)} \frac{1-d_j(a,b)}{1-c(a,b)} & \text{otherwise} \end{cases} \quad (7)$$

The exploitation of the credibility values is known as Distillation. It is an iterative algorithm that selects at each step a subset of alternatives, taking into account the credibility values of the outranking relation previously calculated, $\rho(aSb)$. This procedure yields to two complete pre-orders $O \downarrow$ and $O \uparrow$, called descending and ascending distillation chain respectively. These two complete pre-orders are intersected to generate a final partial pre-order. Although the result of the exploitation is a partial pre-order, to facilitate the interpretation or the management of large sets of data it is also possible to build a complete ranking of the alternatives from the partial pre-order at each of the non-elementary nodes of the hierarchy, by generating a complete pre-order from the partial pre-order (Del Vasto-Terrientes et al., 2015b).

ELECTRE-III-H is a decision aiding method that has two important features:

– A veto threshold that permits to establish the maximum loss allowed when comparing two alternatives on some indicators. Thus, when a criterion strongly disagrees with the assertion aSb, independently of its relative weight with regard to the rest of the criteria, no improvement of the performance of a over b nor deterioration of b over a in other criteria can compensate this veto effect. In that way, we can avoid the compensative effect of other operators, such as weighted average or AHP.
– The management of imprecision and uncertainty by means of the use of discrimination thresholds, which allows taking into account the imperfect nature of the determination of evaluations of the indicators.

The main difference to other ELECTRE methods is that ELECTRE-III-H uses these thresholds both at the elementary level and the intermediate level. When aggregating partial pre-orders (in upper levels of the hierarchy) the thresholds are defined in terms of rank order values. Thus, depending on the number of alternatives the final decision-maker can define the number of rank order positions that should be considered indifferent. It is also important that veto is only applied in relation to their brothers (i.e. the other criteria with the same parent ancestor). This is a remarkable difference with respect to the use of methods that do not consider sub-groups.

3 Characterization and properties of the outranking relation in ELECTRE-III-H

This section studies some mathematical properties of the ELECTRE-III-H method in depth in order to build a valued binary outranking relation $S : A \times A$ from a set of partial pre-orders. These partial pre-orders are generated during the decomposed hierarchical analysis of the decision problem when following the tree of criteria defined by the decision maker. Thus, this operation is the core of the ELECTRE-III-H method presented in Del Vasto-Terrientes et al. (2015b).

Previous works have introduced a common framework and characterization for constructing outranking relations (Bouyssou et al., 1997; Greco et al., 2001; Pirlot, 1997), or concordance and discordance measures (Bouyssou and Pirlot, 2009; Dubois et al., 2003) in the classic approach.

Hereinafter, partial pre-orders are the result of applying the ELECTRE-III-H method for the intermediate criteria, but the same properties are fulfilled if the partial pre-order is obtained from any other procedure, or even if directly given by the decision-maker.

Before the analysis of the properties of the ELECTRE-III-H method, a study of the four possible binary relations and their contribution to the assertion of the outranking relation aSb under different conditions is made in Section 3.1.

Let $D \subseteq G$ be a set of intermediate criteria on G that are the direct descendants of a given g_i, where $D = \{g_{i.1}, g_{i.2}, ..., g_{i.x}\}$. Let us assume that each element $g_{i.j} \in D$ is associated to a weight w_j that indicates its relative importance with respect to the rest of the descendants of g_i, to preference thresholds ($q_j(a)$, $p_j(a)$, and $v_j(a)$), and has a partial pre-order O_j containing the binary preference structure of the alternatives in set A. For each pair of alternatives (a, b), the binary relations $\phi_j \in \{P, I, P^-, R\}$ connect them in O_j. Let us denote as $\rho_D(a, b)$ the credibility index of the outranking relation aSb in the set of criteria D. We denote $aSb = true$ if $\rho_D(a, b) > 0$.

3.1 Characterization of aSb in terms of P, I, P^- and R

In this section, we study the fulfilment of the outranking relation S under different preference relations observed on the partial pre-orders that are aggregated. The conditions for holding aSb (i.e., $\rho_D(a, b) > 0$) are given in terms of rank order values and indifference, and preference and veto thresholds.

3.1.1 Preference and indifference relations, P and I

Proposition 1 *Given two alternatives a, $b \in A$, aSb if $\forall j$, $a\phi_j b$ where ϕ_j=$\{P \vee I\}$.*

Proof The relations P and I fully support the outranking relation S. For all the partial pre-orders O_j, if aPb or aIb, we have

$\forall j$, $c_j(a\phi_j b) = 1$ and $d_j(a\phi_j b) = 0$,

so that:

$\forall j, d_j(a, b) < c(a, b)$, being $c(a, b)$=1.

This results in $\rho_D(a, b) = 1$.

3.1.2 Inverse preference relation P^-

Proposition 2 *Given two alternatives a, $b \in A$ and O_j the partial pre-order of $g_{i.j} \in D$, $\neg(aSb)$ if $\forall j$, there is a relation $aP_j^- b$ and $\Gamma_j(a) - \Gamma_j(b) \geq p_j(a)$.*

Proof Given two alternatives $a, b \in A$ and O_j the partial pre-order of $g_{i.j} \in D$, for the case of a binary relation $aP_j^- b$ in which the difference order value of a and b is greater than or equal to $p_j(a)$, the right to veto is activated so that $d_j(aP_j^- b) > 0$ and $c_j(aP_j^- b) = 0$. Then,

$d_j(a, b) > c(a, b) = 0$, resulting in $\rho_D(a, b) = 0$.

Under this condition, a may not outrank b overall when b performs better on all the criteria in D.

Proposition 3 *Given two alternatives a, $b \in A$ and O_j the partial pre-order of $g_{i.j} \in D$, aSb if $\forall j$, $aP_j^- b$ and $\Gamma_j(a) - \Gamma_j(b) < p_j(a)$.*

Proof Let alternatives a, $b \in A$ and O_j be the partial pre-order of $g_{i.j} \in D$, for all the pairs of binary relations $aP_j^- b$ and all the differences of the order value a and b is less than $p_j(a)$, then:

$\forall j$, $c_j(aP_j^- b) > 0$ and $d_j(aP_j^- b) = 0$.

So that,

$\forall j, d_j(a, b) < c(a, b) \in (0, 1]$, resulting in $\rho_D(a, b) > 0$.

3.1.3 Incomparability relation R

The incomparability relation gives no clear support to the outranking aSb, resulting in fuzzy outranking relations with credibility in (0, 1). Taking into account that the values of partial concordance and discordance indices are respectively in the range of $[k^c - \alpha,\ k^c + \alpha]$ and $[k^d - \alpha,\ k^d + \alpha]$, these indices do not fully agree or reject the relation aSb.

We analyze the conditions where aSb holds for incomparability relations. We assume that $\lambda \geq k^c - \alpha \Rightarrow aSb$. As a reminder, the partial concordance has been defined as:

$$c_j(a, b) = k^c + \frac{(\Gamma_j(b) - \Gamma_j(a) - q_j(b)) \times \alpha}{(p_j(b) - q_j(b)) + (n - 2)}$$

Proposition 4 *Given two alternatives a, $b \in A$, aSb if $\forall j$, $aR_j b$ and $\Gamma_j(b)$ - $\Gamma_j(a)$ - $q_j(b)$=0.*

Proof Having alternatives a, $b \in A$, if the binary relation $aR_j b$ holds and $\Gamma_j(b)$ - $\Gamma_j(a)$ - $q_j(b) = 0$ for all O_j in D, we have

$\forall j$, $c_j(aR_j b) = k^c = \frac{2}{3}$ and $d_j(aR_j b) = 0$.

Then,

$c(a, b) = k^c$ and $\forall j, d_j(a, b) < c(a, b)$, resulting in $\rho_D(a, b) = k^c$.

Proposition 5 *Given two alternatives a, $b \in A$, $\rho_D(a, b) \in (k^c, k^c + \alpha]$ if $\forall j$, $aR_j b$ and $\Gamma_j(a) - \Gamma_j(b) \leq q_j(b)$.*

Proof Having alternatives a, $b \in A$, if the binary relation $aR_j b$ holds and $\Gamma_j(b)$ - $\Gamma_j(a) > q_j(b)$ for all O_j in D, the numerator of the concordance indices expression is always positive, increasing the base value k^c, such that:

$\forall j$, $k^c \geq c_j(aR_j b) > \frac{2}{3}$ and $d_j(aR_j b) = 0$.

Then,

$\forall j, d_j(a, b) < c(a, b)$, resulting in $\rho_D(a, b) \in (k^c, k^c + \alpha]$.

Proposition 6 *Given two alternatives a, $b \in A$, $\rho_D(a,b) \in [k^c - \alpha, k^c)$ if $\forall j$, aR_jb and $p_j(b) \geq \Gamma_j(a)$ - $\Gamma_j(b) > q_j(b)$.*

Proof Having alternatives a, $b \in A$, if the binary relation aR_jb holds and $\Gamma_j(b)$ - $\Gamma_j(a) > q_j(b)$ and $\Gamma_j(a) - \Gamma_j(b) < p_j(b)$ for all O_j in D, the numerator of the concordance indices expression is always negative, decreasing the base value k^c, such that:

$\forall j$, $k^c - \alpha \leq c_j(aR_jb) < \frac{2}{3}$ and $d_j(aR_jb) = 0$.

Then,

$\forall j, d_j(a,b) < c(a,b)$, resulting in $\rho_D(a,b) \in (k^c, k^c + \alpha]$.

When analysing the case below, let us remember that the value of the discordance index is given by the following equation:

$$d_j(a,b) = k^d + \frac{(\Gamma_j(b) - \Gamma_j(a) - q_j(b)) \times \alpha}{(p_j(b) - q_j(b)) + (n-2)}$$

Proposition 7 *Given two alternatives a, $b \in A$, $\neg(aSb)$ if $\forall j$, aR_jb and $\Gamma_j(a)$ - $\Gamma_j(b) > p_j(b)$.*

Proof Having alternatives a, $b \in A$, if the binary relation aR_jb holds and $\Gamma_j(a)$ - $\Gamma_j(b) > p_j(b)$ for all O_j, the difference between the rank order value of alternative a with respect to b is larger than the permitted threshold $p_j(b)$, making an opposition to the outranking relation aSb. Thus, we have:

$\forall j$, $c_j(aR_jb) = 0$ and $d_j(aR_jb) = [k^d - \alpha, k^d + \alpha]$,

then $\forall j, d_j(a,b) > c(a,b)$, resulting in $\rho_D(a,b) = 0$.

3.2 Properties of ELECTRE-III-H

This section provides the main properties of the construction of the outranking relation for partial pre-orders in the ELECTRE-III-H method. The properties studied are the usual conditions imposed on social choice procedures and aggregation operators.

- **Neutrality with respect to criteria:** The credibility of aSb does not depend on the order of consideration of the criteria. For any permutation $D' = \sigma(D)$:

  $$\rho_D(a,b) = \rho_{D'}(a,b), \text{ so that } aS'b \Rightarrow aSb$$

  Proof This property is fulfilled by $\rho_D(a,b)$ because the product and addition operators are commutative.

- **Monotonicity:** If aSb and $\Gamma(a)$ improves or $\Gamma(b)$ deteriorates in O_j, then aSb remains. The outranking relation aSb is preserved based on the improvement or deterioration of the rank order value of alternatives a and b, respectively.

  Proof Considering alternatives a and b, if aSb, the following cases may occur:
  - If aP_jb and a improves or b deteriorates, then the relation between them is still aP_jb, therefore aSb holds as $c_j(a,b) = 1$,
  - If aI_jb and a improves or b deteriorates, then aI_jb turns into aP_jb and aSb holds as $c_j(a,b) = 1$,
  - If aP_j^-b and a improves or b deteriorates, then the following cases may occur:
    - If aP_j^-b turns into aP_jb or aI_jb, then $c_j(a,b) = 1$ and aSb holds,
    - If aP_j^-b remains, the difference $\Gamma_j(a) - \Gamma_j(b)$ gets smaller, so that according to Eq. 5 and Eq. 6, $c_j(a,b)$ increases or $d_j(a,b)$ decreases respectively.
  - If aR_jb and a improves and b deteriorates then the following cases may occur:

- If aR_jb turns into aP_jb or aI_jb, then aSb holds as $c_j(a,b) = 1$,
- If aR_jb remains but a improves and b deteriorates with respect to other alternatives in O_j, the difference $\Gamma_j(a) - \Gamma_j(b)$ shrinks, so that according to Eq. **??** and Eq. **??**, $c_j(a,b)$ increases or $d_j(a,b)$ decreases respectively.

– **Pareto principle:** Alternative a does not outrank alternative b if b is strictly better than a on all criteria. This property is also known as Pareto efficiency or unanimity. As the $\Gamma(\cdot)$ function measures the performance of an alternative in a partial pre-order (i.e., its rank order value), we can write this property as follows:

$$\forall j,\ \Gamma_j(b) < \Gamma_j(a) - p_j(a), \text{ then } \neg(aSb)$$

Proof By construction, in any partial pre-order, if $\forall j, \Gamma_j(b) \leq \Gamma_j(a) - p_j(a)$, only discordant indices $d_j(a,b) > 0$ are calculated, thus refuting aSb.

– **Independence of irrelevant alternatives:** The relation aSb relies on the rank order values calculated from the preference relation matrix $\mathcal{M}$. The addition/deletion of an alternative in the set A, or even the modification of the performance of another alternative in A, results in the modification of the preference relation matrix $\mathcal{M}$. Then, the independence property of the relation aSb may not be fulfilled.

$A' = A \cup \{k\}$, then aSb does not imply $aS'b$.

Proof Let us consider $A = \{a, b, c\}$ where $\Gamma_j(b) < \Gamma_j(c) < \Gamma_j(a)$ and $A' = \{a, b, c, k\}$ where $\Gamma_j(b) < \Gamma_j(k) < \Gamma_j(c) < \Gamma_j(a)$.
Let be $\beta = \Gamma_j(a) - \Gamma_j(b) = 1$ in O_j and $\beta' = \beta + 1$ in O'_j. If $q_j, p_j(a) = 0, v_j(a) = 2$, being $\beta' = v_j(a) > \beta$, then aSb and $\neg(aS'b)$.

The non-fulfilment of the property of "independence of irrelevant alternatives" leads to the problem known as "rank reversal" or "rank invariance principle". It is a phenomenon that occurs when in a decision process a ranking O is obtained from a set of alternatives A and the addition/deletion/modification of alternative(s) generates a ranking O', which reverses the rank order of several pairs of alternatives previously obtained in O. For example, let us suppose that alternatives a and b are ranked 1st and 2nd respectively in O, and then adding a non-optimal alternative z results in a new ranking O' in which b and a are ranked 1st and 2nd respectively. The issue of rank reversals lies at the heart of many debates in MCDA field (Figueira and Roy, 2009; Saaty and Sagir, 2009; Wang and Triantaphyllou, 2008; Wang and Luo, 2009). This phenomenon has been studied and analyzed for ELECTRE methods in Wang and Triantaphyllou (2008).

Detractors of rank reversal claim the existence of a pre-existing truth that must not be changed under the same conditions (f.i., weights, and thresholds), as in the case of utility-based decision making. However, other authors such as Figueira and Roy (2009) state that the very nature of real-world problems and the fact such problems are frequently modelled using poor data (i.e., ordinal scales), makes finding the "real" ranking a rather utopian quest. Several authors have indicated that in practice rank reversal phenomena occur frequently and is not necessarily bad (Saaty and Vargas, 1984; Vargas, 1994; Roy, 1972). In Roy (1972), an example illustrating that such phenomena can be interpreted quite naturally is presented and suggests that forcing the independence property may be unrealistic in many real-world case studies.

The main reason for the rank reversal is that when adding, deleting, or modifying an alternative in A, the credibility matrix changes. As the classic ELECTRE-III method does not fulfil the property of independence with respect to irrelevant actions, the comparison between two alternatives is conditioned by the remaining alternatives. If for example, one of the remaining alternatives is modified, then the exploitation procedure is applied to a different credibility matrix, which may naturally result in a different recommendation.

The same happens in the hierarchical version ELECTRE-III-H because the calculation of the relation aSb from partial pre-orders does not fulfil the independence of irrelevant alternatives. As the rank order value of the alternatives is related to changes of the rank order value of the remaining alternatives, any change from a lower level will affect the preference relation matrix $\mathcal{M}$

from which the partial concordance and discordance indices are calculated, possibly leading to a different order of the alternatives.

This section has presented two important analyses of the ELECTRE-III-H method. First, the consistency between the preference relations found in the partial pre-order and the outranking relation constructed upon them. Second, we prove the fulfilment of neutrality, monotonicity, and the Pareto principle by the outranking relation. Finally, a discussion about the independence of irrelevant alternatives on the construction of the outranking index and its effect in rank reversals in the exploitation has been given. This last issue highlights the importance of setting alternatives to be compared from the beginning, with the participation of the stakeholders and decision-maker.

4 Problem statement

Wind power is an important renewable energy source with positive social and economic benefits. In addition, the technology is deemed to be revolutionary and has been selected as the main power source for Europe's 2020 goals to attain 20% renewable energy in their energy mix (European Commission, 2013). It has recorded a consistent growth of global installed wind generation capacity by more than 20% a year, in the last 10 years of the world (Torres Sibille et al., 2009). The implementation of wind-parks is inserted in the Catalonia Energy Plan for the year 2010 to analyze the current consumption of renewable energy and the potential production for the year 2010, to develop a model to evaluate projects in an economic and technical way, and finally to state the goals of energy production from renewable energy sources.

The rapid development in wind energy technology has led to consider it a suitable alternative to conventional energy systems. It is argued that wind energy is one of the most promising tools for confronting global warming, being a powerful source of renewable energy with rapid and simple installation, lack of emissions and low water consumption (Yeh and Huang, 2014). Despite investment in this renewable energy has the potential to improve the economic development, especially in rural places as well as public residences, and this energy is more environmentally friendly than conventional energy, it also implies some negative impacts on a local scale. Wind farms have a strong influence on their local environment such as additional noise or the poor integration of turbines into the landscape. These issues are directly tangible and important assets for local people, which will not be easily accepted by them. Consequently, the most appropriate site for wind farms must not harm property values of those who live there.

Wind farm location is a problem that involves multiple and conflicting criteria related to the several opinions and interests. To find the best wind farm location, the relevant economic, social, technical and environmental perspectives must be all taken into account during the decision-making process (Wolsink, 2010; Lee et al., 2009; Enzensberger et al., 2002). Different studies proposed different key factors and indicators involved in wind farm selection regarding stakeholder preferences and location of wind farms. In this section, a real case from the study of Gamboa and Munda (2007) for the analysis of the location of a wind farm in Catalonia is considered. This case study was performed in the counties of *Urgell* and *Conca de Barberá* (Fig. 3). The evaluation criteria and the scores presented in the following subsections come from the Spanish research project by UAB/ICTA[2] based on the technical translation of the needs, preferences, and desires of the social actors.

In this problem, different stakeholders had different expectations and conflicting requirements with each others. Some municipalities and some citizens were in favor of constructing wind farm plants according to two preliminary projects as a good opportunity to increase their income and to improve social services and some others were against it. The main social and economic stakeholders participating in this project are detailed in Table 2.

4.1 Study of the alternatives

Two mountain areas were considered: *Coma Bertran* (CB) and *Serra del Tallat* (ST) projects. Initially, the three preliminary wind farm site alternatives were considered based only on the

[2] Autonomous University of Barcelona and centre of Environmental Studies (now called Institute of Environmental Sciences and Technologies ICTA)

Fig. 3: *Urgell* and *Conca de Barberà* counties of Catalonia

Table 2: Socio-economic stakeholders in the wind farm project

Actors	**Level of action**
National social actors	Catalan government
	Environmental non-governmental organization
	Enegiá Hidroeleétrica de Navarra (EHN)
	Gerrsa (Promoter of the Coma Bertran project)
Provincial actors	President of the l'Urgell county council
	Political representatives
	Coordinating committee to defend the land
	Platform for Senan
Local-Provincial actors	Municipality of Vallbona de less Monges
	Municipality of Rocallaura
	Municipality of Els Omells de Na Gaia
	Town council of Senan
	Association of friends and neighbours of Montblanquet

technical and economical indicators: CB-Pre, ST-Pre and CBST-Pre. After some discussion among the stakeholders, only CB-Pre was left for evaluation. Later on, other indicators were also added in the study: technical feasibility, wind availability, visual impact of the original proposals and economic viability of the alternatives. Based on these new indicators, three new projects (CB, ST, CBST) were proposed; where CBST is the combination of the Coma Beltran and Serra del Tallat projects. Considering social acceptance and the anxiety some people had about the visual impact of the wind farms, two modified projects L and R were added in the study. These projects take into account the reduction of visual impact of the original proposals. A map of the zone that includes all the possible sites is shown in Fig. 4.

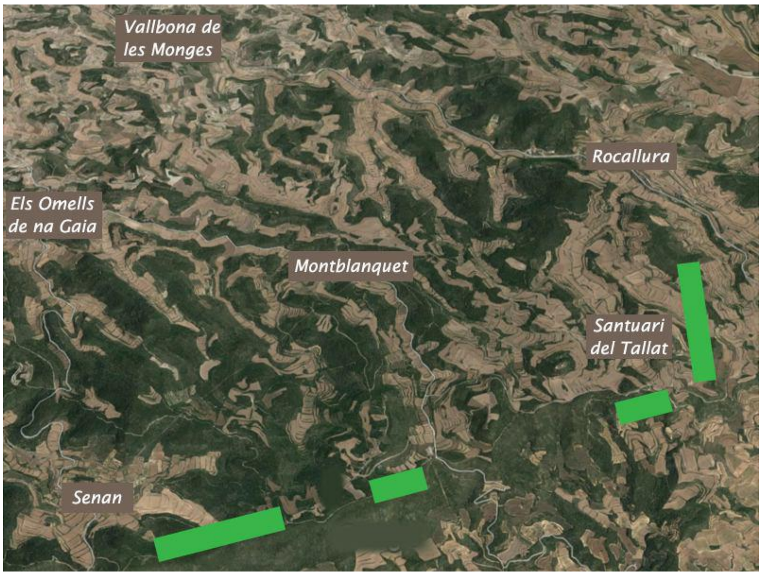

Fig. 4: Technical feasibility zones

The possibility of not constructing a wind park (NP) is also included in this study, as it was considered of interest, which is the *Business as Usual* (BaU) situation. This means maintaining the current situation. The rational behind this alternative is that choosing an alternative with different criteria would be riskier. Once the alternatives were defined, a resume of the main features was discussed with several actors to evaluate their feasibility and the degree of acceptance. Table 3 lists the proposed site alternatives together with their basic description. More details about this set of possible locations and the main features of the parks are given in Table 4. Fig. 5 shows the specific locations of wind mills for each alternative.

Table 3: Alternatives for the location of wind farm

Alternatives
CB-Pre: Coma Bertran Preliminary project.
CB: Coma Bertran project.
ST: Serra del Tallat project.
CBST: Combination of CB and ST projects.
L: Based on CB and ST projects, considers the windmills located at least more than 1.5 km far from population centres and potential tourist attractions (Santuari del Tallat).
R: This option attempts to move the windmills away from population centers presenting higher resistance to the wind farms (Senan and Montblanc).
NP: the possibility of constructing no project at all (Business as usual).

Table 4: Alternatives features

Alternatives	**CB-Pre**	**CB**	**ST**	**CBST**	**L**	**R**	**NP**
Number of windmills	16	11	33	44	26	24	0
Power capacity (MW)	13.6	16.5	49.5	66	39	36	0
Rotor height (m)	55	80	80	80	80	80	80
Blade diameter (m)	58	77	77	77	77	77	77

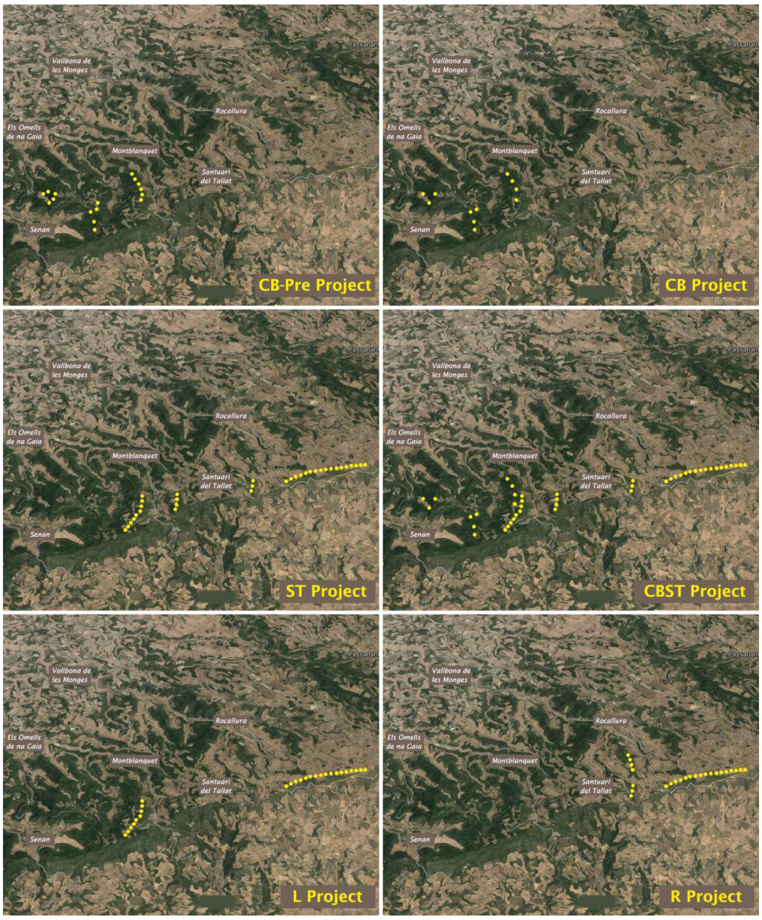

Fig. 5: Locations of windmills

4.2 Hierarchy of criteria

Four different dimensions of the problem have been considered in the analysis of the best wind farm location: economic, technical, social and environmental. The economic and technical criteria were initially considered in the decision process. However, to satisfy all actors involved in this project (such as local people), environmental and social perspectives were included.

Taking into account these four perspectives, alternatives are finally evaluated on the basis of nine indicators, which were defined by combining information from participatory processes, interviews and a review of the projects at regional scale (detailed in Gamboa and Munda (2007)). The set of criteria is given in Table 5. A positive direction of the criteria means that a greater value of the criterion score is preferred to a smaller one, while criteria with negative direction means the opposite, i.e., a smaller value is preferred over a greater one.

Social and ecological criteria: Social issues affect the permission process for project approval and include public acceptance and visual impact. The attitude of people towards wind farm location is different from place to place. In some countries, a lot of developers have been forced to invest on offshore projects because people do not want to see wind turbines near their towns. While it could make economic sense to site a wind farm near an urban centre, the social impact would prevent such proximity. People tend to consider both visual and noise impact as main factors in fuelling social resistance to wind farm development. Activists who oppose wind farm developments have coined slogans like NIMBY (Not in My Back Yard), and BANANA (Build Absolutely Nothing Anywhere Near Anything) in their campaigns (PennWel, 2012). In fact, on the global scale everyone agrees that GHG should be reduced, but on the local scale many people are not willing to suffer the disadvantages.

Table 5: Family of Criteria

Intermediate Criteria	**Elementary Criteria**	Units	**Direction**
Economic	Land owner's income (C_1)	€/year	+
	Economic activity tax (C_2)	€/year	+
	Construction tax (C_3)	€	+
Social	Number of jobs (C_4)	Per person	+
	Visual impact (C_5)	km^2	-
Ecological	Deforestation (C_6)	ha	-
	Avoided CO_2 emissions (C_7)	ton CO_2 /year	+
	Noise (C_8)	$dB(A)$	-
Technical	Installed capacity (C_9)	MW	+

Economic and technical criteria: Economic factors do not only affect the locations of the wind farms but also the sizes of the farms themselves. The economic and technical criteria include site accessibility, proximity to the grid, availability of installation equipment, income and taxes and installed capacity. All these indicators have been considered in this study. The best option is to locate wind farm as close to an existing grid as possible. It is also necessary that the grid can handle the capacity you plan to generate. If not, the wind farm developer or transmission company has to extend it. Wind farms can only be located in areas with good wind regimes, these are sometimes remote or isolated areas, thus the grid improvements turn out to be expensive. Another issue that technically affects generating wind power is installed capacity. The size of a wind farm or the amount of power that can be generated is determined by the capacity that can be installed.

Since these criteria represent four well differentiated needs related to different actors, we propose to construct a decision model that is able to take into consideration these four dimensions. In this direction, we have defined a hierarchy with two different levels of criteria. At the elementary level (the lowest), the nine indicators are taken into account. The intermediate level consists of four criteria: technical, economic, environmental and social. This hierarchical structure of the criteria is shown in Fig. 6, where the intermediate criteria may be understood as intermediate sub-goals, while the root node will be output of the analysis that integrates all the four sub-goals. Notice that there is only one indicator in the group of technical issues (installed capacity), thus, in this case this elementary criterion is connected directly to the root node.

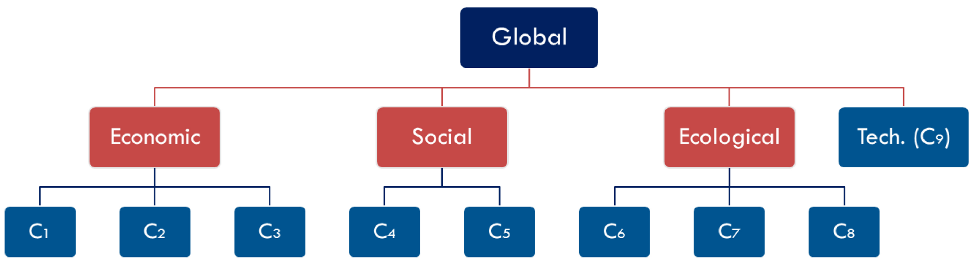

Fig. 6: Hierarchical structure for the wind farm location problem

In the next section, we explain how the ELECTRE-III-H method can be used for the assessment of the suitability of several wind farm locations. This method is especially indicated for this problem because it is able to provide an order structure for each of the sub-goals (economic, social and ecologic) in addition to the global one. With this information the final decision-maker will be able to deeply analyze all the different factors that are important in this problem in order to find the best location.

5 Results and robustness analysis

In this section, the use of ELECTRE-III-H method in the wind farm case study is explained to show how this method is appropriate for this problem. The performance matrix for the elementary criteria is presented in Table 6 (Gamboa and Munda, 2007). The indifference threshold, shown in the same table, was defined according to the experts' knowledge.

Table 6: Performance matrix for the elementary criteria

Criteria	**Indifference threshold** $q_j(a)$	**CB-Pre**	**CB**	**ST**	**CBST**	**L**	**R**	**NP**
C_1	10000	48000	33000	99000	132000	78000	72000	0
C_2	10000	12750	15470	46410	61880	36570	33750	0
C_3	12000	61990	55730	96520	152250	81890	67650	0
C_4	1	2	1	4	5	3	3	0
C_5	10	76.057	71.465	276.55	348.015	220.4	163.29	0
C_6	1.5	8.04	8.1	6.6	14.7	3.9	2.6	0
C_7	2000	4680	6010	19740	25750	14740	13760	30000
C_8	3	14.64	23.86	18.6	23.84	20.88	14.66	0
C_9	5	13.6	16.5	49.5	66	39	36	0

In order to apply ELECTRE-III-H, several parameters have to be fixed for each criterion, both at the elementary and intermediate levels. Note that the stakeholders were involved in the choice of the criteria and assessment of the alternatives during the decision-making process. Nevertheless, although the application that we present in this paper is based on this data, they have not been able to actively participate in this later hierarchical analysis. Instead, the research team defined different configurations of weights and thresholds from the base case in order to obtain solutions from the various perspectives of the stakeholders. In this section, we first present a comparison between classic ELECTRE-III and ELECTRE-III-H results in a base scenario, and then we make an analysis of how the variation of these parameters influences the order among the different sites.

First, we define a *base scenario*. Weights will be equal for the intermediate and elementary levels, and so no priority is defined for them. At the elementary level, the indifference thresholds given in Table 6 are used, the preference is set equal to indifference $p_j(a) = q_j(a)$ and we work without veto on all criteria. With this base configuration, a comparison between classic ELECTRE-III and ELECTRE-III-H is performed. To this end, let us consider the problem without the hierarchy of criteria, such that all criteria are aggregated at the same level as in the classic ELECTRE-III method. The partial pre-order obtained by the classic ELECTRE-III method is shown in Fig. 7.

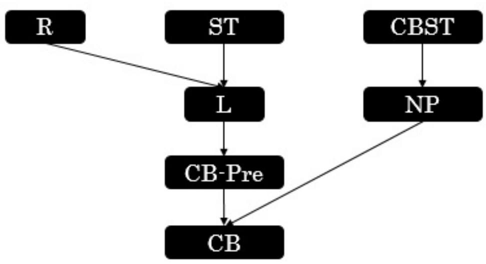

Fig. 7: classic ELECTRE-III Base Scenario Result

We can observe that alternative R is not comparable to alternatives ST and CBST. With this classic approach, we cannot find a clear *best alternative* for the decision problem. Notice also that NP is not comparable to many options. This large number of incomparabilities is probably due to the fact that we are merging information from very different indicators, referring to different parts of the problem (i.e. jobs, income, noise, etc.). In this approach, all criteria vote in favor of "a outranks b" or abstain (no discordance is applied as a veto is avoided), hence it is easier to have a draw on the number of votes. Moreover, the decision-maker cannot know which dimensions are more favorable to each alternative. Consequently, as we have already proposed before, we will now solve the problem using the ELECTRE-III-H method based on the hierarchical structure of the criteria already presented in Fig. 6.

We set $q_j(a)$=0, $p_j(a) = 0$ at the intermediate level, and again we avoid veto on all intermediate criteria. With this configuration the ELECTRE-III-H method will exclusively base the result on the majority voting opinion. The rankings obtained at the intermediate criteria are:

– Economic: CBST > ST > L > R > CB-Pre > CB > NP,
– Ecological: NP > R > L=ST > CB-Pre=CBST > CB,
– Social: R=CB-Pre > NP=ST=CBST > CB=L,
– Technical: CBST > ST > R=L > CB=CB-Pre > NP.

At the root node, these four rankings (i.e. the corresponding partial pre-orders) are merged with ELECTRE-III-H, and the overall ranking obtained with this base scenario is shown in Fig. 8.

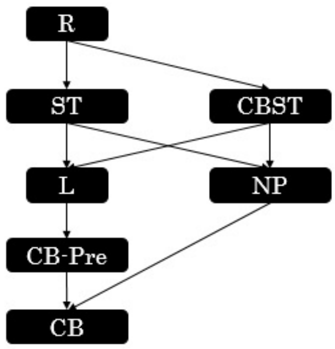

Fig. 8: ELECTRE-III-H Base Scenario Result

Now, we can find more preference relations among the options than in the first classic non-hierarchical approach. With the hierarchical treatment of the criteria, alternative R is considered as the best option for wind farm location because of its moderate performance on all criteria. Compared to other alternatives such as CBST (even though CBST has very good economic and technical criteria because of the weak performance on the ecological criteria) it is considered worse and is placed in second position in the ranking. This can be evaluated thanks to the partial results obtained by the hierarchical method, as shown later for each intermediate criteria in Fig. 9. Moreover, using ELECTRE-III-H (see. Fig. 9) and following the performance matrix (Table 6), we can conclude that the incomparability between alternative R with respect to alternatives ST and CBST may be because of the poor economic performance of R and installed capacity criteria and its better performance on the ecological and social criteria.

In order to fully show the power of ELECTRE-III-H, in the rest of this section other scenarios will be considered, to study the impact of the different parameters at the elementary and intermediate levels.

Due to the uncertainty of the predictions, three scenarios (base, tolerant and strict) have been defined. The difference is in the degree of veto at the elementary and intermediate levels (see Table 7). The base scenario is defined without veto at the intermediate and elementary levels, which are denoted by BI and BE. The second scenario introduces a low degree of veto at the elementary level (TE), and considers two possibilities at the intermediate level: tolerant veto (TI_1) and no veto (TI_2). The last scenario is more strict with veto at both levels with the same structure mentioned in tolerant scenario in SI_1, SI_2 and SE. These scenarios are analyzed in subsection 5.1. Notice that in this initial study, the indifference and preference thresholds at the intermediate level are set to 0, due to the reduced number of alternatives (i.e. giving a maximum of 6 in the rank order value). Other thresholds will be considered in section 5.2.

Table 7: Three Scenarios

Scenarios	Levels	$q_j(a)$	$p_j(a)$	$v_j(a)$
Base Scenario	Intermediate level (BI)	0	0	no
	Elementary level (BE)	X_1	Y_1	no
Tolerant Scenario (Low Veto)	Intermediate level (TI_1 & TI_2)	0	0	TI_1=6, TI_2=no
	Elementary level (TE)	X_1	Y_1	$Max - Min$
Strict Scenario (High Veto)	Intermediate level (SI_1 & SI_2)	0	0	SI_1=3, SI_2=no
	Elementary level (SE)	X_1	Y_1	$\frac{Max-Min}{2}$

5.1 Testing different preference thresholds at the elementary level

In the first analysis, using the constant thresholds of the intermediate level $q_j(a)$=$p_j(a) = 0$, we set $q_j(a)$ at the elementary level as defined in Table 8. Then, we compare the results obtained at the intermediate level, in order to understand the effect of changing the preference threshold values on the elementary indicators. We consider two situations: $p_j(a) = q_j(a)$ and $p_j(a) = 2q_j(a)$ (see Table 8).

Table 8: Indifference and preferences thresholds

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
q	10000	10000	12000	0	10	1.5	2000	3	5
$p = q$	10000	10000	12000	0	10	1.5	2000	3	5
$p = 2q$	20000	20000	24000	1	50	3	4000	6	10

We first analyze the rankings obtained at the three intermediate criteria (see Fig. 9). In order to compare the results, we have assigned each alternative a rank position following the relations in the partial pre-order (being 1 the top of the ranking, the best option). We can see that CBST is the winner according to the economic criteria, NP is the winner according to the ecological criteria and CB-Pre is the winner according to the social criteria always. We can also see that the ranking is quite stable for the economic criteria when changing the p threshold, as well as for the three scenarios (basic BE, tolerant TE and strict SE). This shows that the economic issues define a clear order among the sites. For the ecological criteria, the ranking is also quite stable in all cases. On the contrary, the social criteria show more variation in the positions, as well as many ties (which may be due to indifference or incomparability). Note that some overlaps occur between the lines of Fig. 9.

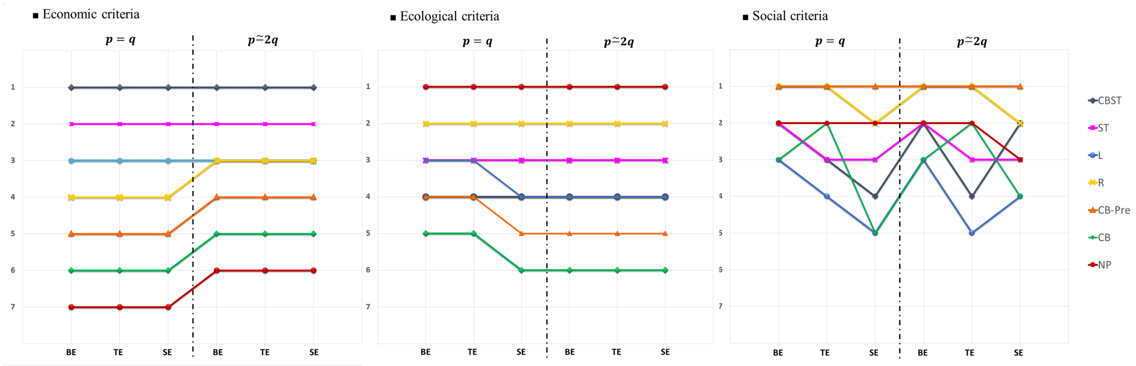

Fig. 9: Hierarchical rankings at the elementary level

We then obtained the global ranking at the root node by aggregating those three rankings together with the technical criterion (C9). The results are shown in Fig 10. Let us remember that the initial ranking obtained in a base scenario had R in the first position R > ST = CBST > L = NP > CB-Pre > CB and this corresponds to the left-most ranking in this figure. When increasing the preference (second analysis on the right part of the figure), the base global ranking is: R > CBST > ST > NP = L = CB-Pre > CB. It can be observed that for stricter parameters, CBST becomes the best alternative available because it has a good performance in economic criterion as well as in terms of installed capacity. For non-stricter parameters, alternative R is generally included as the best alternative when applying no veto (BE) and tolerant scenarios. This indicates that the use of the veto threshold at the intermediate level plays an important role in the final result.

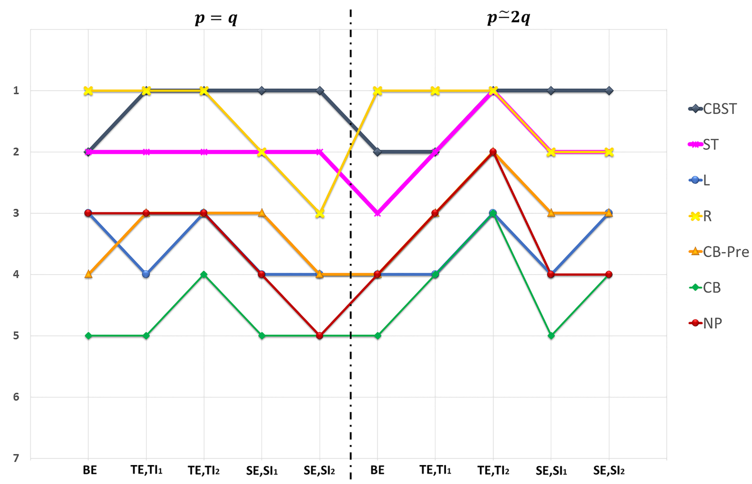

Fig. 10: Global rankings of two analyses

5.2 Testing different preference thresholds at the intermediate level

In this section, an analysis on the sensitivity to the preference threshold at the intermediate level is presented. A new setting is defined for a more tolerant framework by changing the $p_j(a)$ threshold, from 0 to 1, at all the three intermediate criteria. At the elementary criteria we take the second case presented in the previous section, with the indifference threshold values given in Table 8 and $p_j(a) = 2q_j(a)$.

In this case, for tolerant scenarios (i.e., TE, TI_1 and TE, TI_2), we can observe that alternative CBST attains worse positions in the ranking when compared to R and ST alternatives when $p = 1$ (see Fig. 11). In fact, this is the least stable alternative. We also see differences in the position when comparing the results with $p = 0$ (left) with $p = 1$ (right), which indicates that the preference threshold at the intermediate levels also has a noticeable influence on the final result. The positions in the strict cases (comparing SI_1, SI_2) are the same for most of the alternatives, and CBST is still considered the best option.

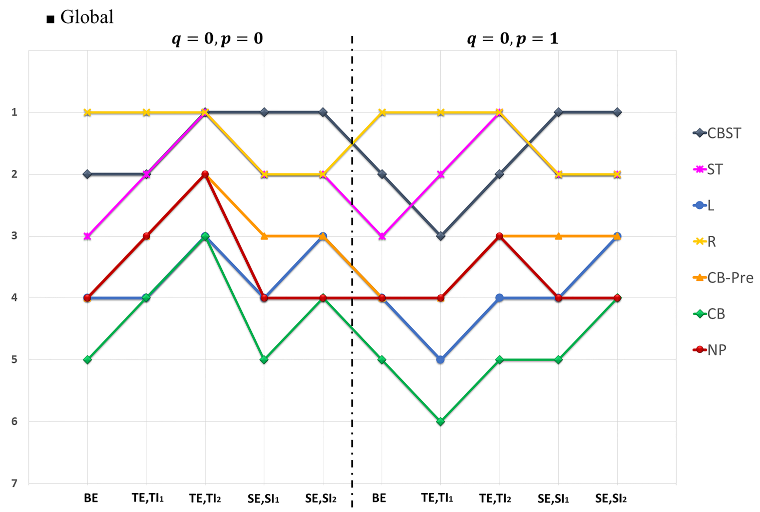

Fig. 11: Global rankings with more preference threshold at the intermediate level

We will now more closely study the influence of the parameters at the intermediate level. We will consider $p = 2q$ and the fixed TE scenario at the elementary level. The partial pre-orders of the alternatives obtained at the three intermediate criteria are shown in Fig. 12. In this case, the social criteria pre-order shows more incomparabilities between alternatives because of their different scores. For example, CB is incomparable with NP, ST, and CBST. According to social issues, project L has the worst position, although it is not so bad on the economic or even the ecological criteria. We can see that R is always in good positions, including third, second, and first position in different rankings. This shows that R is the most stable alternative among the best overall options (including CBST and ST). However, we must take into account that for the installed capacity criterion, alternatives CBST, ST, and L perform better.

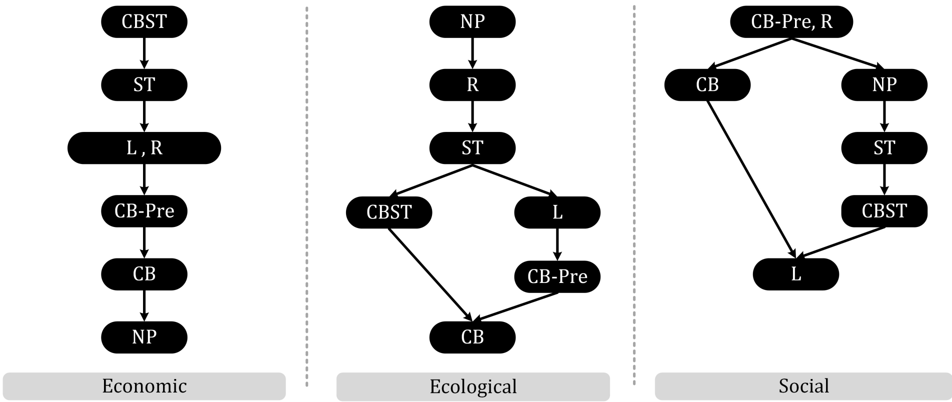

Fig. 12: Partial pre-orders at the intermediate level (TE, $p = 2q$)

We will now demonstrate how the ELECTRE-III-H methodology constructs a global partial pre-order from the pre-orders depicted in Fig. 12, plus the technical elementary criterion. First, threshold parameters for the intermediate criteria have to be set. Four cases have been defined in Table 9 using various preference, indifference, and veto thresholds in terms of the number of alternatives ($m - 1 = 6$). Notice that we increase the thresholds from Case 1 to Case 4, being increasingly tolerant each time. However, the thresholds for "installed capacity" are fixed in the base configuration.

The results obtained for these cases from lower to higher q and p thresholds are displayed in Fig. 13. We observe that in Case 1 we have more indifference and incomparability relations among the alternatives. Considering Case 1, we can observe three alternatives ranked first, including ST, CBST and R; with R being incomparable with respect to CBST and ST. However, in Case 2 ST is positioned second in the ranking, while CBST and R remain first and incomparable. This incomparability is due to the good performance of CBST for the economic and installed capacity criteria, while R has an excellent performance for the ecological and social criteria. By increasing $q_i(a)$ and $p_i(a)$ thresholds in Cases 3 and 4, we exaggerate the uncertainty and decrease the role of the discordance, and so the alternatives become more difficult to be differentiate in terms of preference. The decision about the order is left in hands of the installed capacity criterion (which is not modified in the tests). In fact, in Case 4, the ranking is directly given by the performance of the alternatives for the installed capacity criterion.

Table 9: Threshold configurations at intermediate level

Thresholds	Case1	Case2	Case3	Case4
$q_i(a)$	0	1	3	6
$p_i(a)$	3	3	6	6
$v_i(a)$	6	6	6	6

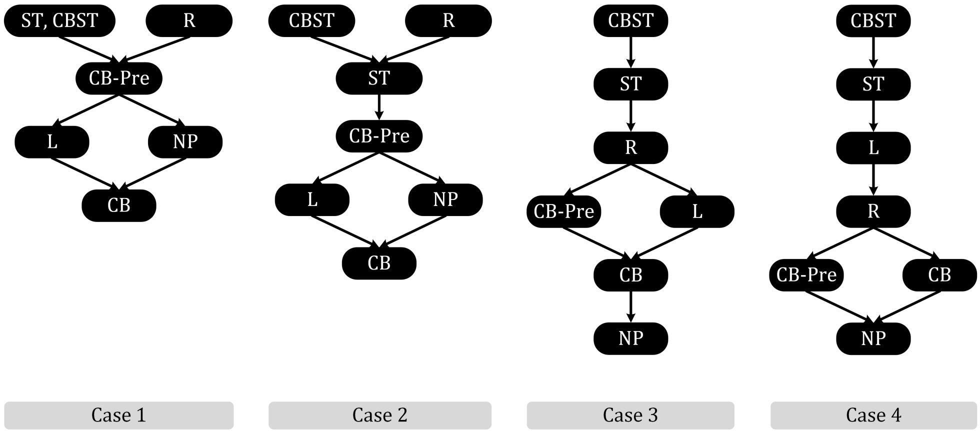

Fig. 13: Partial pre-orders for the different cases at the root level

5.3 Giving different power to the intermediate criteria by means of veto and weights

In the previous section we studied the neutral case in which all the sub-goals had the same influence in the final result, because all of them had the same weight, which represents the same voting power, and also the same threshold values. This section analyzes how the decision-maker can change the decision model in order to give more power to one of the three main intermediate criteria: economic, ecological and social.

First, we will keep the same weight for all these criteria and will change the veto power, which is the right of opposition to the opinion of the other criteria. Afterwards, we will give more weight to one of the criteria instead of veto power, in order to check if the voting power given by weights provides the same result.

For the first test, three configuration scenarios of threshold values in the intermediate criteria are considered, including the "Strict veto for economic concern", "Strict veto for ecological concern" and "Strict veto for social concern". These scenarios are presented in Table 10. Note that when the preference and veto thresholds are increased, we are decreasing the strength of opposition to the assertion aSb. Thus, only one of the criteria is strict in each scenario. At the elementary level, we set $p = 2q$ and we will consider the TE and SE scenarios defined as before.

Table 10: Strict veto of each criteria at the intermediate level

Scenarios	**Criteria**	$q_j(a)$	$p_j(a)$	$v_j(a)$
Economic strict scenario				
	Economic	0	0	1
	Social	0	2	6
	Ecological	0	2	6
Ecological strict scenario				
	Economic	0	2	6
	Social	0	2	6
	Ecological	0	0	1
Social strict scenario				
	Economic	0	2	6
	Social	0	0	1
	Ecological	0	2	6

Results in Fig. 14 show that the rankings are generally stable. Strict veto on the economic criteria ranked CBST and R as the best options. CBST is the best alternative based on economic factors, but because of its poor performance on the rest of the criteria, R is tied in first position. In general, R performs well in all the scenarios considered, except when there is strict veto in social criterion and strict setting in elementary criteria as well (SE). In fact, R is the best alternative as the ecological indicators are the best (excluding alternative NP) and it also performs well for the economic and social criteria.

A similar situation can be found when using more veto power for social concerns - where CB-Pre ranked second when strict elementary parameters (SE) were applied. CBST also becomes the first alternative in the ranking, rather than R, because the base scenario and SE alternatives CBST and R are both ranked second, while for the TE alternative, CBST is ranked fourth and R is first (see Fig. 9).

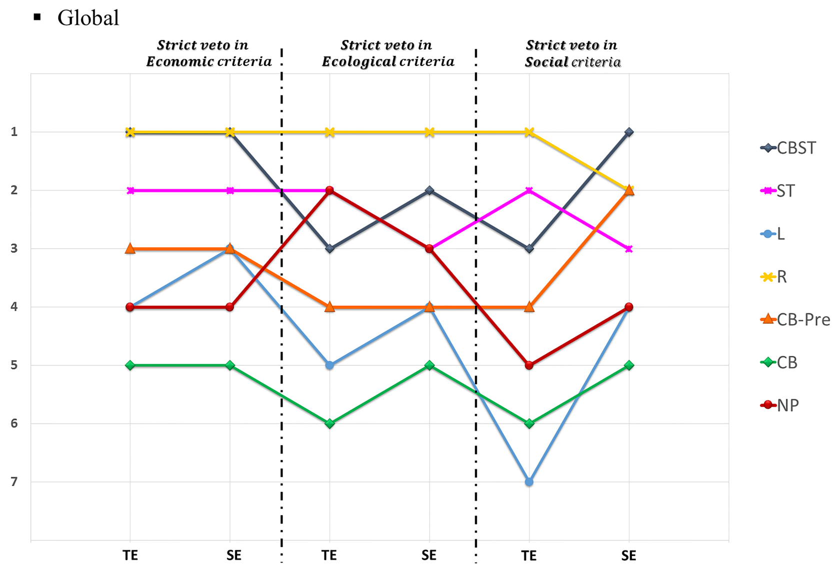

Fig. 14: Global rankings with different veto power on the intermediate criteria

As explained before, to complete this analysis another test by increasing the weights of the criteria instead of using more strict veto has been considered. This may correspond to a situation where one of the dimensions of the problem needs to play a more important role in the final decision. In this test, the results of using different importance coefficient at the intermediate level demonstrates that weights also have an influence in the global rankings. To make this test, we have given five times more weight to one criterion than the others. The thresholds are now set to be the same as the base case (BE) and $p_j(a) = 2q_j(a)$.

The partial pre-orders obtained at global level are presented in Fig. 15. They can be compared to the partial pre-orders obtained using strict veto on one the same criterion, which are displayed in Fig. 16. When comparing this analysis with the one incorporating the strict veto for each criteria, we can observe that they do not have a similar effect on final rankings. For instance, using more weight for the social criteria drastically changes the outcomes of the method compared to veto power. Using more weight, we obtained three alternatives tied in second place (CB-Pre, ST, and CBST) including the incomparability of CB-Pre and ST, while veto power increases clearly establish an order, i.e. CBST $>$ ST $>$ CB-Pre. We can also see differences in the economic and ecological criteria. Comparing the results obtained by increasing the weights and using strict veto shows that these two parameters play different roles in the decision analysis procedure. On the one hand, weights change the majority value when measuring concordance (establishing a trade-off with the rest of the criteria). On the other hand, veto acts in a different step of the procedure, in the discordance stage, in a way that completely neutralizes the rest of the criteria.

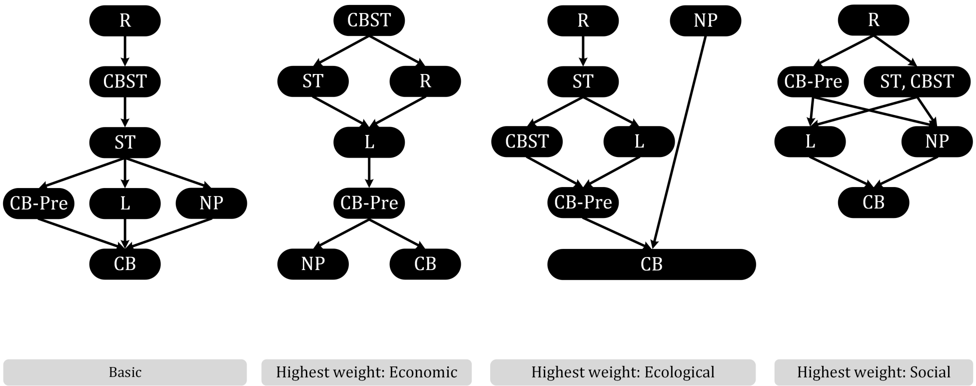

Fig. 15: Global results with different criteria weights at the intermediate level

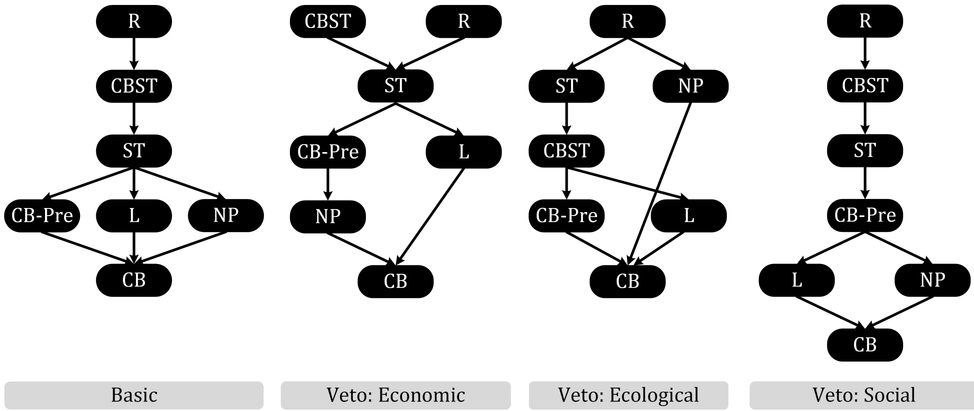

Fig. 16: Global results with different veto power for the criteria at the intermediate level

After performing all these tests, we find that the best and the worst options can be changed depending on the different configurations of parameters. Yet, in general, it is clear that Project R (which moves the windmills away from the villages) is the alternative recommended by the ELECTRE-III-H method. The reason is, alternative R does not have the extremely good or extremely bad values for any criterion, but it is not vetoed in any of the cases. By contrast, the worst project found in the different tests is CB (Coma Bertran), which proposes putting the windmills between two villages. These results also demonstrate the advantages of a hierarchical approach during the decision making process. In comparison with the result obtained by Gamboa and Munda (2007), CBST was the best and NP was the worst alternatives in their study. Their results are shown with a best ranking, however in this study, the parameters have been defined to illustrate that different results reflect different settings. For instance, NP is not always the worst option regarding ecological aspects.

6 Conclusions

Energy planning problems are suited to the use of MCDA for evaluating environmental sustainability. These complex problems usually involve multiple conflicting criteria and multiple decision-makers (Tsoutsos et al., 2009; Karvetski et al., 2011). The process for deciding the location of the wind turbines is one of these complex real-world problems. It involves different social actors with their own concerns and priorities.

In this paper, we propose a model of evaluation to find a suitable location for a wind farm that considers a hierarchy of the criteria organized according to four main dimensions: economic, technological, social and environmental. The paper shows that the ELECTRE-III-H method is appropriate for finding a solution, because it can integrate the information following a hierarchical structure. The main reason is that this method enables modeling the main points of view as intermediate sub-goals. It is then possible to obtain preference orders from among the options at different levels of the hierarchy and study how each sub-goal influences the global result. ELECTRE-III-H provides useful information that enables a comparison of the different sub-goals, which is impossible under a non-hierarchical analysis such as the one conducted with the classical ELECTRE-III method. This hierarchical ELECTRE method has been proposed recently in the literature Del Vasto-Terrientes et al. (2015b). In this paper we have analyzed its mathematical properties and made a characterization of its behavior, showing that it is consistent with the information of the partial pre-orders aggregated at each step.

In the rest of the paper, a case study in a region of Catalonia has been considered. We have seen that in a classic analysis with a flat structure of the criteria, ELECTRE-III cannot establish preference relations among the different options. In contrast, when using a hierarchical analysis with ELECTRE-III-H, the best solution found places for the windmills away from the population. This option is best in most of the scenarios with various discrimination and veto thresholds, as well as with different weighting policies. However, the remaining options change the position when parameters are modified. This indicates that it is important to spend time in defining the appropriate values for these parameters, in order to fine-tune and construct a model that represents the needs of decision-makers. However, the paper is not intended to give a solution to this particular case study, but to show the effectiveness of this hierarchical approach instead of the classic approach (in one level) and to demonstrate how this method is a good fit for these set of problems. The parameters have been defined to illustrate that different results appear according to different settings, but we do not establish which is the best. In addition, this paper is also focused on demonstrating how a decision problem analysis varies depending on the priorities of the decision-maker when modeled using hierarchies of the criteria. For instance, we obtain a general/overall result, as well as partial results (f.i., economical or ecological) that may help the decision-maker in the analysis of parameters, weights, etc.

Furthermore, the decision-maker can also establish the best sites when only a subgroup of the criteria is considered. In this case study, using only the economic benefits of constructing the wind farm, the best option is the CBST combination (installing numerous windmills in Coma Bertran and Serra del Tallat). For the ecological indicators (i.e. deforestation, CO_2, and noise avoidance) the best project is ST (Serra del Tallat). When only social concerns are considered, the best option is CB-Pre (preliminary project in Coma Bertran, placing the windmills between the villages of Senan and Montblanquet). It can be seen that it is impossible to simultaneously optimize all criteria.

The compromise solution found in this study is Project R, which proposes a reduced number of windmills away from Senan and Montblanquet. The paper also shows that the importance of one criterion for the final decision can be given with a large weighting, or with a strict veto power. However, each case has a different influence on the model and final decision.

Two main directions will be considered for future work. Firstly, and from a theoretical point of view, an automatic system for finding the values of parameters that best reflects significant changes in preferences can be developed. Secondly, the application of ELECTRE-III-H to other real problems in selecting renewable energy alternatives is being considered.

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